A New Class of $SO(10)$ SUSY-GUT Models with TeV Scale W_R, Z'

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B.D., R. N. Mohapatra, *Phys. Rev. D* **81**, 013001 (2010) [arXiv:0910.3924 [hep-ph]];

arXiv:1003.6102 [hep-ph].

Outline

Introduction

- LHC set to explore the nature of TeV scale New Physics beyond the SM.
- SUSY (especially MSSM) – one of the prime candidates.
- An attractive feature of MSSM: Gauge coupling unification.
- Broader picture: **Can any other new physics co-exist with TeV scale SUSY without spoiling the unification at high scale?**
- An interesting possibility: weak interactions conserve parity asymptotically $\Longrightarrow$ Left-Right symmetry [with gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$] at high scale.
- A natural extension of SM/MSSM to explain small neutrino masses via seesaw mechanism: $B-L$ breaking by RH neutrino.

Low Scale LR Seesaw

- **Type I seesaw**: SM singlet Majorana RH neutrino (N). [Minkowski '77; Yanagida '79; Glashow '79; Gell-Mann, Ramond, Slansky '80; Mohapatra, Senjanović '80]

$$\mathcal{L}_{\rm mass} = (\overline{L} M_D N + {\rm h.c.}) + N M_N N$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}; \quad m_\nu^{\rm light} = -M_D M_N^{-1} M_D^T$$

Sub-eV light neutrino mass $\Longrightarrow$ TeV scale M_N possible only for $M_D \lesssim m_e$.

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- **Inverse seesaw**: Mostly Dirac N. Add another gauge singlet S. [Mohapatra '86; Mohapatra, Valle '86]

$$\begin{aligned} \mathcal{L}_{\rm mass} &= (\overline{L} M_D N + \overline{N} M_N S + {\rm h.c.}) + S\mu S \\ \mathcal{M}_\nu &= \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_N \\ 0 & M_N^T & \mu \end{pmatrix}; \\ m_\nu^{\rm light} &\simeq \left(M_D M_N^{-1}\right) \mu \left(M_D M_N^{-1}\right)^T \quad \text{for } \mu \ll M_N \end{aligned}$$

TeV scale M_N even with large $M_D \sim m_t$ due to the additional small parameter μ.

Grand Unification Prospects of TeV Scale Seesaw

- How does seesaw physics affect unification?
- Can seesaw physics co-exist with MSSM at TeV scale?
- $SO(10)$: Natural GUT for LR seesaw as

$$SO(10) \supset SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

  and its **16**-dim. spinor representation contains all the matter fermions, including the RH neutrino.
- Does TeV scale LR unify at $SO(10)$ scale? If so, then LHC can possibly probe grand unification!!
- TeV type I seesaw does not grand unify! [Majee, Parida, Raychaudhuri, Sarkar '07-08; Kopp, Lindner, Niro, Underwood '09]
- **New: TeV inverse seesaw does unify to $SO(10)$.** [B.D., Mohapatra'09]

Highlights

- A new SUSY $SO(10)$ scenario with coupling unification.
- Simple fermion mass and mixing rules due to $SO(10)$ symmetry.
- Small neutrino masses by inverse seesaw mechanism.
- Radiative breaking of both $B - L$ and electroweak symmetries.
- TeV scale W_R, Z' accessible at LHC. Also, distinct trilepton signal.
- Testable phenomenological consequences in the leptonic sector (non-unitarity, LFV, leptonic CPV etc.).
- Consistent with current proton decay bounds.

Inverse Seesaw in $SO(10)$

- Need two sets of SM singlet fermions N, S.
- All the SM fermions and RH neutrino are in a single $\mathbf{16}_F$ spinor rep.
- Add a gauge singlet fermion $\mathbf{1}_F$ to play the role of S.
- Schematically, the $SO(10)$ invariant Yukawa superpotential is

$$W_Y = h\mathbf{16}_F\mathbf{16}_F\mathbf{10}_H + f\mathbf{16}_F\mathbf{1}_F\overline{\mathbf{16}}_H + \mu\mathbf{1}_F\mathbf{1}_F$$

- Inverse seesaw structure for the neutrino mass matrix:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & hv_u & 0 \\ hv_u & 0 & f\overline{v}_R \\ 0 & f\overline{v}_R & \mu \end{pmatrix}; \quad (\text{with } \overline{v}_R \equiv \langle\overline{\mathbf{16}}_H\rangle,\ v_u \equiv \langle\mathbf{10}_H\rangle)$$

$$m_\nu^{\text{light}} \simeq \mu\left(\frac{hv_u}{f\overline{v}_R}\right)^2 \ \text{ and } \ m_\nu^{\text{heavy}} \simeq f\overline{v}_R \quad \text{for } \mu \ll v_u \ll \overline{v}_R$$

- Typical TeV-scale inverse seesaw: $\overline{v}_R \sim$ few TeV, $v_u \sim 100$ GeV (electroweak scale). So sub-eV m_ν possible for $\mu \sim$ keV.

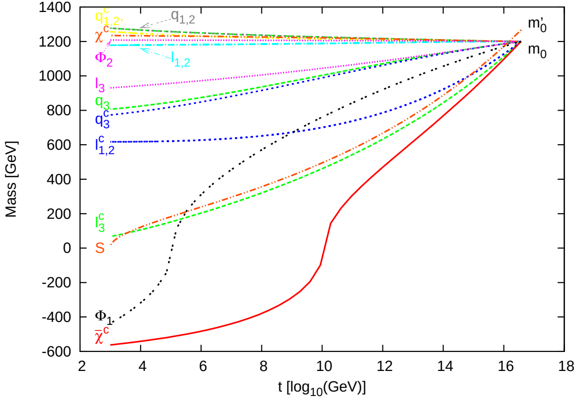
Breaking $SO(10)$

- We consider the breaking chain

$$SO(10) \xrightarrow{M_G} \underbrace{\mathbf{3}_c\mathbf{2}_L\mathbf{2}_R\mathbf{1}_{B-L}}_{\text{(SUSYLR)}} \xrightarrow{M_R} \underbrace{\mathbf{3}_c\mathbf{2}_L\mathbf{1}_Y}_{\text{(MSSM)}} \xrightarrow{M_{\text{SUSY}}} \underbrace{\mathbf{3}_c\mathbf{2}_L\mathbf{1}_Y}_{\text{(SM)}} \xrightarrow{M_Z} \mathbf{3}_c\mathbf{1}_Q$$

- $SO(10)$ is broken by $\mathbf{45}_H$ and $\mathbf{54}_H$ fields.
- $B-L$ is broken by $\mathbf{16}_H + \overline{\mathbf{16}}_H$ fields (and not by $\mathbf{126}_H$).
- Electroweak symmetry is broken radiatively by $\mathbf{10}_H$ fields.
- Fermion masses generated via Yukawa couplings to $\mathbf{10}_H$.
- Need *at least two* $\mathbf{10}_H$ multiplets to get a realistic fermion mass spectrum.
- Also need to have a light vector-like color triplet of $\mathbf{45}_H$ to satisfy proton decay constraints for unification scale.

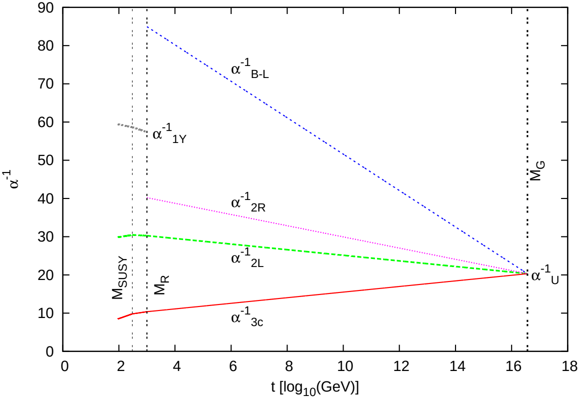
Radiative Breaking of $B-L$ and EW Symmetries



[B.D., Mohapatra '10]

- Start with a universal positive squared spartner mass at GUT scale.
- RGEs turn $m^2_{\Phi_1}$, $m^2_{\bar{\chi}^c} < 0$ at low scale, while leaving all other squared masses positive.
- Much like in MSSM, $m^2_{H_u}$ turns negative to give rise to radiative EWSB.

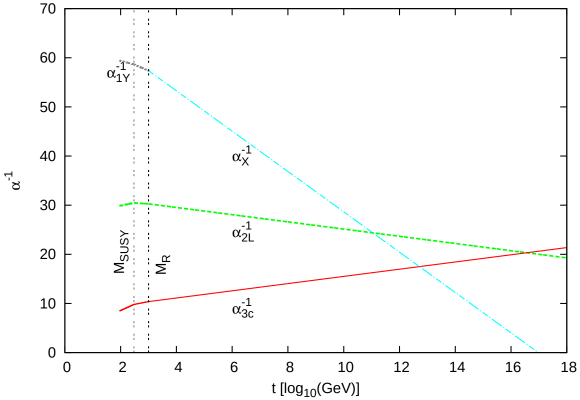
Gauge Coupling Unification



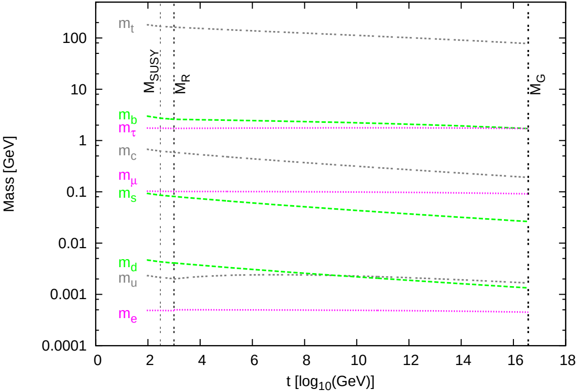
$$[n_{10} = 2,\ n_{16_L} = 0,\ n_{16_R} = 2 \text{ and } M_{\rm SUSY} = 300 \text{ GeV}, M_R = 1 \text{ TeV}]$$

[B.D., Mohapatra '09]

Compare with Type-I Case



Fermion Mass Spectrum

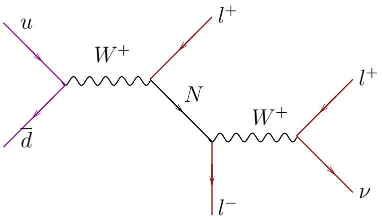


Generic $SO(10)$ GUT relations satisfied:

$$\frac{m_b}{m_\tau} \simeq 1, \quad \frac{m_\mu}{m_s} \simeq 3, \quad \frac{m_e}{m_d} \simeq \frac{1}{3}$$

LHC signatures

- TeV scale heavy RH neutrinos $\Longrightarrow$ can be produced on shell at hadron colliders.
- Pseudo-Dirac fermions (with small Majorana component), unlike in type I case (purely Majorana).
- The "smoking gun" LHC signature for type-I and III scenarios, $pp \to l^\pm_\alpha l^\pm_\beta$+jets (LNV), will be suppressed in this case.
- Instead, one can expect to get observable LNC (but LFV) effects in channels with small SM background.
- **Most distinctive signature is the trilepton event $pp \to l^\pm_\alpha l^\pm_\beta l^\mp_\gamma \nu(\overline{\nu})$+jets.**



[del Aguila, Aguilar-Saavedra, de Blas '09]

Non-Unitarity of the Neutrino Mixing Matrix

- Generalized PMNS matrix: $\mathcal{N} \simeq (1-\eta)U_{\rm PMNS}$ where $\eta \simeq \frac{1}{2}\left(M_D M_N^{-1}\right)\left(M_D M_N^{-1}\right)^\dagger$.
- Current 90% C.L. bounds on $|\eta|$: [Antusch, Baumann, Fernández-Martínez '09]

$$|\eta| < \begin{pmatrix} 2.0\times 10^{-3} & 3.5\times 10^{-5} & 8.0\times 10^{-3} \\ 3.5\times 10^{-5} & 8.0\times 10^{-4} & 5.1\times 10^{-3} \\ 8.0\times 10^{-3} & 5.1\times 10^{-3} & 2.7\times 10^{-3} \end{pmatrix}$$

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- Predictions of our model (for diagonal M_N):

m_{N_1}	m_{N_2}	m_{N_3}	$\|\eta_{e\mu}\|$	$\|\eta_{e\tau}\|$	$\|\eta_{\mu\tau}\|$
1.1 TeV	1.1 TeV	1.1 TeV	3.7×10^{-7}	1.5×10^{-5}	6.5×10^{-5}
100 GeV	100 GeV	1.1 TeV	7.9×10^{-7}	1.6×10^{-5}	8.9×10^{-5}
30 GeV	30 GeV	2.1 TeV	6.7×10^{-6}	4.4×10^{-5}	3.2×10^{-4}

- $|\eta_{e\mu}|$ **bound reachable at future neutrino factories (sensitivities up to** 3.2×10^{-7}**)** [van der Schaaf '03] **and also in the PRISM/PRIME project.** [PRIME Working Group '05]
- **The largest value of $|\eta_{\mu\tau}|$ may also be accessible to short baseline neutrino oscillation experiments.** [Malinsky, Ohlsson, Xing, Zhang '09]

Lepton Flavor Violation Effects

- The heavy neutrinos N_i mediate the rare lepton decays, $l_\alpha^- \to l_\beta^- \gamma$ with

$$\mathrm{BR}(l_\alpha \to l_\beta \gamma) \simeq \frac{\alpha_W^3 s_W^2 m_{l_\alpha}^5}{256\pi^2 M_W^4 \Gamma_\alpha} \left| \sum_{i=1}^{3} \mathcal{K}_{\alpha i} \mathcal{K}^*_{\beta i} I \left(\frac{m_{N_i}^2}{M_W^2} \right) \right|^2$$

[Ilakovac, Pilaftsis '95]

- Amplitude $\propto \left| \left(\mathcal{K}\mathcal{K}^\dagger\right)_{\alpha\beta} \right| \simeq \mathcal{O}(|\eta_{\alpha\beta}|)$.
- Compare with the type I case, where $\mathcal{K}\mathcal{K}^\dagger \simeq \mathcal{O}\left(m_\nu M_R^{-1}\right)$ is strongly suppressed. [Deppisch, Valle '05]

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- Compare with the type I case, where $\mathcal{K}\mathcal{K}^\dagger \simeq \mathcal{O}\left(m_\nu M_R^{-1}\right)$ is strongly suppressed. [Deppisch, Valle '05]
- Predictions in our model:

$$\mathrm{BR}(\mu \to e\gamma) \simeq 3.5 \times 10^{-16}$$
$$\mathrm{BR}(\tau \to e\gamma) \simeq 1.1 \times 10^{-13}$$
$$\mathrm{BR}(\tau \to \mu\gamma) \simeq 2.0 \times 10^{-12}$$

- $\mu \to e\gamma$ **within reach of future experiments, e.g. PRISM/PRIME (sensitivities down to** 10^{-18}**).**

Leptonic *CP* Violation

- Governed by the full PMNS matrix through the Jarlskog invariant

$$J^{ij}_{\alpha\beta} = \mathrm{Im}(\mathcal{N}_{\alpha i}\mathcal{N}_{\beta j}\mathcal{N}^*_{\alpha j}\mathcal{N}^*_{\beta i})$$

(with $\alpha, \beta = e, \mu, \tau;\ i, j = 1, 2, 3;\ \ \alpha \neq \beta,\ i \neq j$)

- To leading order in θ_{13} and η, $J^{ij}_{\alpha\beta} \simeq J + \Delta^{ij}_{\alpha\beta}$, where the unitary part is

$$J = c_{12}c^2_{13}c_{23}s_{12}s_{13}s_{23}\sin\delta$$

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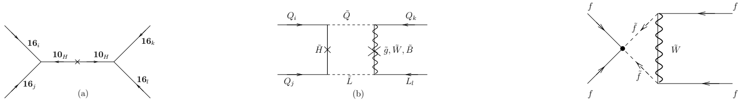
$$J = c_{12}c_{13}^2 c_{23} s_{12} s_{13} s_{23} \sin\delta$$

- Predictions for $\Delta J_{\alpha\beta}^{ij}$ in our model:

$$\Delta J_{e\mu}^{12} \simeq -2.4 \times 10^{-6},\ \ \Delta J_{e\mu}^{23,31} \simeq -2.7 \times 10^{-6},$$
$$\Delta J_{\mu\tau}^{23,31} \simeq 2.7 \times 10^{-6},\ \ \Delta J_{\tau e}^{12} \simeq 7.1 \times 10^{-6}$$

- **Can be the dominant source of *CP*-violation in the leptonic sector for vanishing θ_{13} and/or vanishing δ case.**

Proton Decay Rates



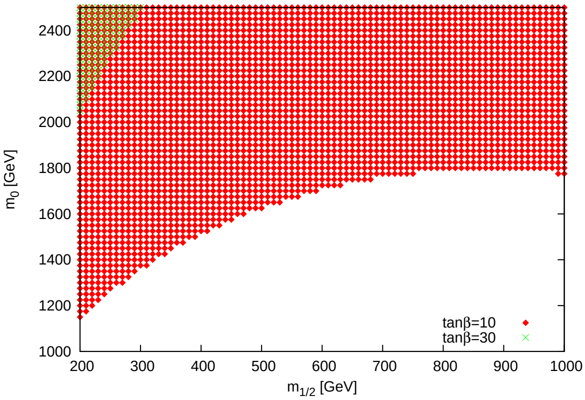
Dimension-5 operator contribution involving wino exchange:

$$\tau(p \to Ml) \simeq \frac{(4.42 \times 10^{33}\ \text{years})}{|f(F,D)|^2} \left(\frac{10^{-14}}{|\mathcal{C}|^2}\right) \left(\frac{200\ \text{GeV}}{m_{\tilde{W}}}\right)^2 \left(\frac{M_{\tilde{f}}}{1\ \text{TeV}}\right)^4$$

Decay mode	Experimental lower limit ($\times 10^{33}$ yr)	Predicted upper limit ($\times 10^{33}$ yr)	
		$\tan\beta = 10$	$\tan\beta = 30$
$p \to K^+\overline{\nu}$	2.3	2.3	2.3
$p \to K^0\mu^+$	1.3	399.3	738.8
$p \to K^0 e^+$	1.0	1.3×10^3	49.7
$p \to \pi^0 e^+$	10.1	5.8×10^3	230.0
$p \to \pi^0\mu^+$	6.6	2.4×10^4	1.3×10^4
$p \to \pi^+\overline{\nu}$	0.025	1.5	0.8

Constraints on Universal Parameters

Allowed region in the $m_0 - m_{1/2}$ plane satisfying both proton decay and EWSB constraints:



Need $M_{\tilde{f}} \geq 1.2$ (2.1) TeV for $\tan\beta = 10$ (30) to satisfy the $p \to K^+\overline{\nu}$ constraint.

Summary

- A new $SO(10)$ SUSY-GUT scenario with TeV scale LR inverse seesaw.
- Successful gauge coupling unification and realistic fermion mass and mixing pattern.
- Radiative symmetry breaking of $B-L$ and electroweak symmetries.
- TeV scale W_R and Z' interesting for colliders.
- TeV scale pseudo-Dirac RH neutrinos giving rise to distinctive collider signatures.
- Leptonic non-unitarity bounds accessible at future neutrino oscillation experiments.
- Similar accessibility for $\mu \to e\gamma$ decay rate.
- Non-negligible leptonic CP-violation effects.
- Consistent with proton decay constraints for squark mass $\gtrsim \mathcal{O}(\text{TeV})$.